

Demonstrated Processes for Limit of Technology Nutrient Removal

Charles B. Bott

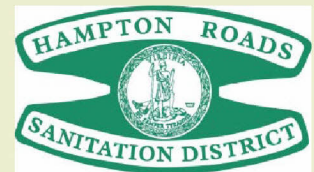
Hampton Roads Sanitation District &

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Coauthors: Denny Parker, B&C; J. B. Neethling, HDR; Amit Pramanik,
WERF; and Sudhir Murthy, DCWASA

WERF Nutrient Challenge Meeting

Wednesday July 1, 2009



- WERF (Nutrient Challenge)
- WEF
 - Municipal Wastewater Treatment Design Committee
 - Research Symposium
- Steering Committee
 - Denny Parker, Brown and Caldwell, co-PI
 - Sudhir Murthy, DCWASA
 - JB Neethling, HDR, WERF Nutrient PI
 - Amit Pramanik, WERF Senior Program Director
- Plant Managers and Volunteers

Project Organization

- Phase I – ended with WEFTEC 2008 Workshop
 - Guidance and oversight from Denny, Sudhir, JB, and Amit
 - Bott and VMI – contractor
 - 11 plants analyzed
 - No student involved
 - In-kind support from all involved
- Phase II – to be completed with report to WERF
 - Denny and Bott – Co-PIs
 - HRSD Municipal Assistance Program – contractor
 - HRSD subcontracts to VMI and B&C
 - 12 plants being analyzed now
 - HRSD providing in-kind and cash support

Purpose : Develop Answers to Critical Questions for LOT Plants

1. To what extent can existing technology reliably achieve low effluent limits with respect to total nitrogen or total phosphorus?
2. How is “low” defined? The Limit of Technology (LOT) is loosely described at TN of 3.0 mg/L and TP of 0.1 mg/L. Can this be achieved and on what averaging period and with what reliability?
3. To what degree do regional climatic differences influence performance?
4. Do some technologies out perform others in meeting low effluent nutrient limits?
5. What are rational statistical bases for permit writing for LOT plants?
6. What plant features ease operators tasks?

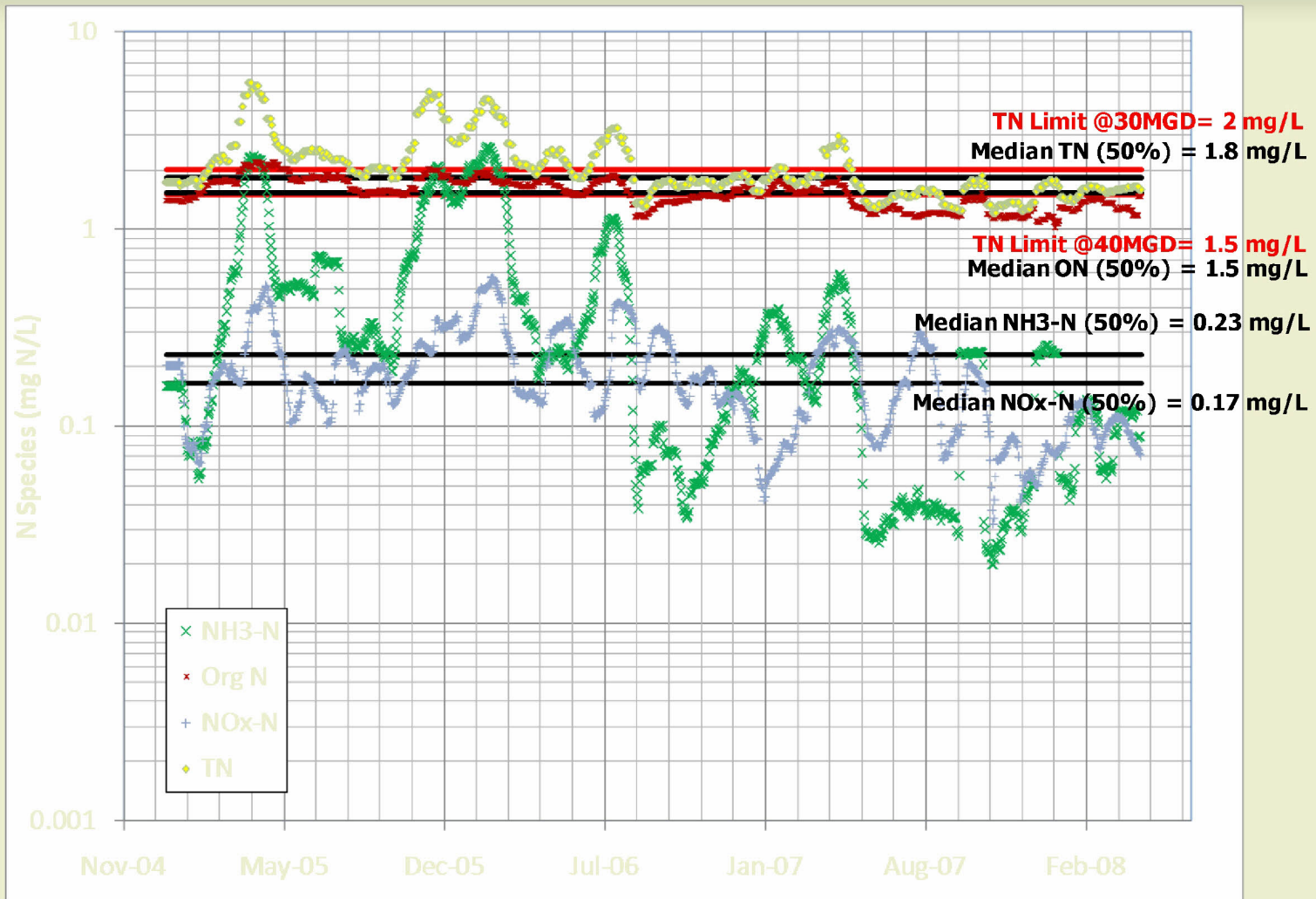
Treatment Plants Considered

Nutrient	Process Type	Facility	Climate	Comment
N	Separate Stage N Removal			
	Suspended growth	River Oaks, FL	Warm	08 survey
	Suspended growth	Western Branch, WSSC	Cold	09 survey
	Attached growth	Truckee Meadows Water Reclamation, NV	Cold	08/09 survey
	Attached growth	Scituate, MA	Cold	09 survey
N	Combined N Removal			
	Suspended growth	Eastern Water Reclamation Facility, FL	Warm	08 survey
	Suspended growth	Parkway WSSC	Cold	08 survey
	Suspended growth	Hammon, NJ	Cold	09 survey
	Suspended growth	Piscataway, WSSC	Cold	09 survey
	Suspended growth	Clearwater FL	Warm	09 survey
N	Multiple Stage N Removal			
	Suspended/attached growth	Fiesta Village, FL	Warm	08 survey
P	Single Stage Chemical Addition			
	Ballasted sedimentation	Iowa Hill WRF, CO	Cold	08 survey
	Lamellas/filtration	Wayne Hill, GA	Warm	08 survey
	MBR	Cauley Creek, GA	Warm	08 survey
	BioP, and tertiary clarifiers and filter	Pinery, CO	Cold	09 survey
	Tertiary clarifiers/filters	ASA, VA	Cold	09 survey
P	Multiple Stage Chemical Addition			
	Suspended, tertiary clarifiers and filters	Clark County, NV	Moderate	08 survey
	Suspended, tertiary clarifiers and filters	Rock Creek, OR	Cold	08 survey
	Primary treatment/Suspended growth	Blue Plains, DC	Cold	08 survey
P	Biological phosphorus removal, minimal or no chemicals			
	Suspended growth	Kelowna, BC	Cold	09 survey
	Suspended growth	Kalispell, MT	Cold	09 survey
Ammonia	Limit of Technology			
	Suspended growth (oxidation ditch)	Kalkaska, MI	Cold	09 survey
	TF/SC followed by NTFs	Littleton/Englewood, CO (tent)	Cold	09 survey
	Suspended growth, Bio P plant	Utoy Creek, Atlanta	Moderate	09 survey

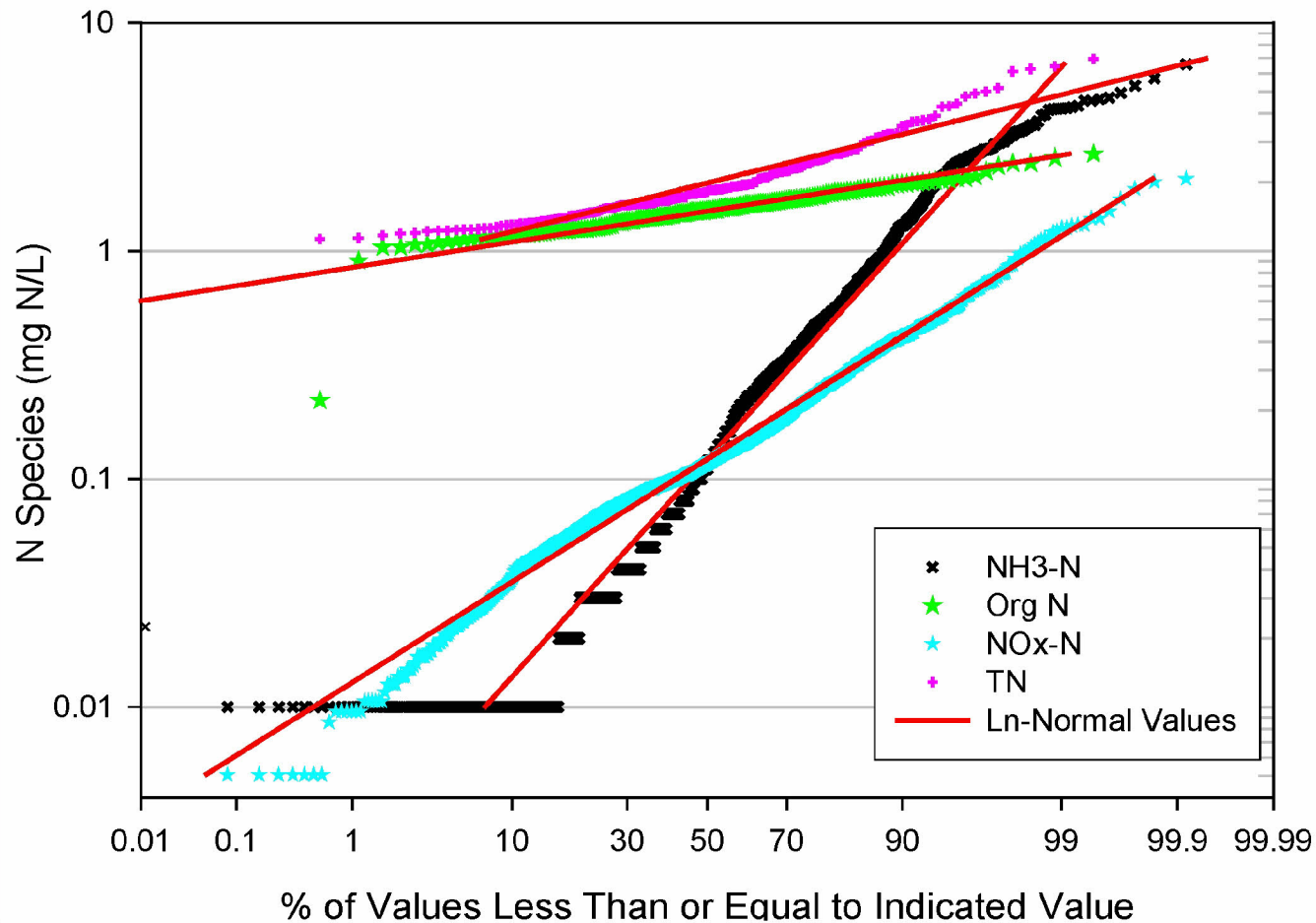
What Affects Reliability?

- BOUNDARY CONDITIONS
- Wastewater Characteristics and Seasonal Issues
- Process
 - Single versus multiple barrier
 - Complexity
 - Suspended solids removal
 - Excess capacity
- Upsets
 - Chemical supply problems
 - Duration caused by cold or wet weather
 - Equipment, construction, etc
 - Toxic inhibition
- Sampling Frequency
- Values below the detection/reporting limit

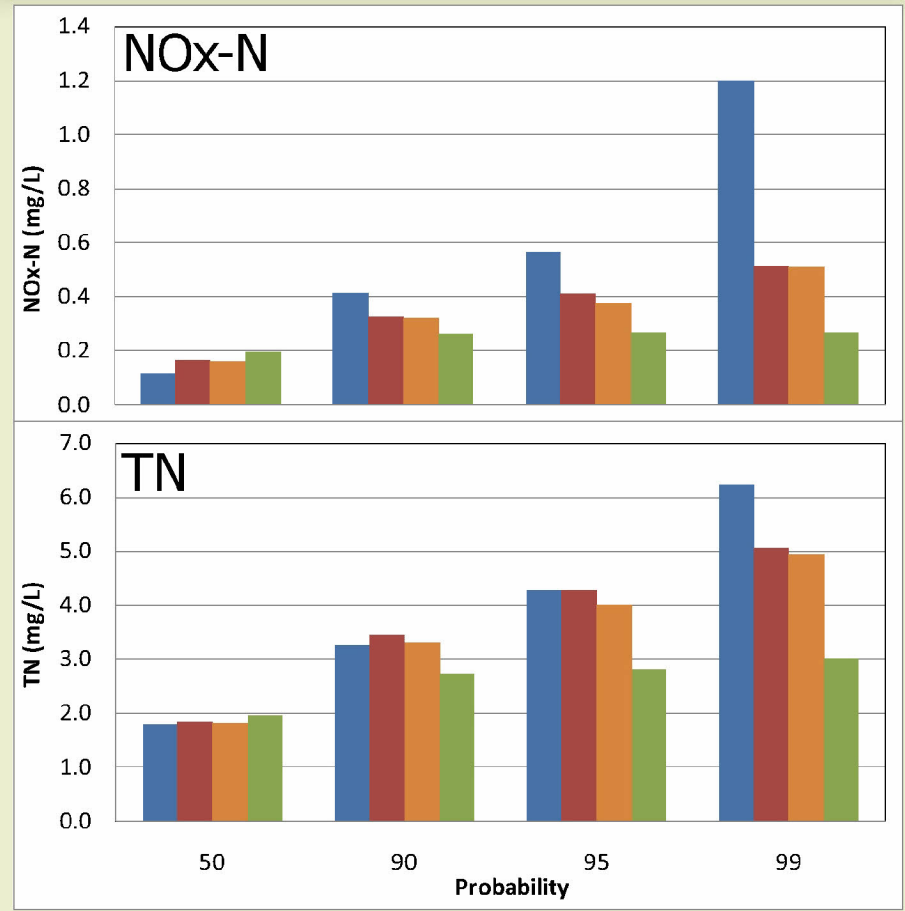
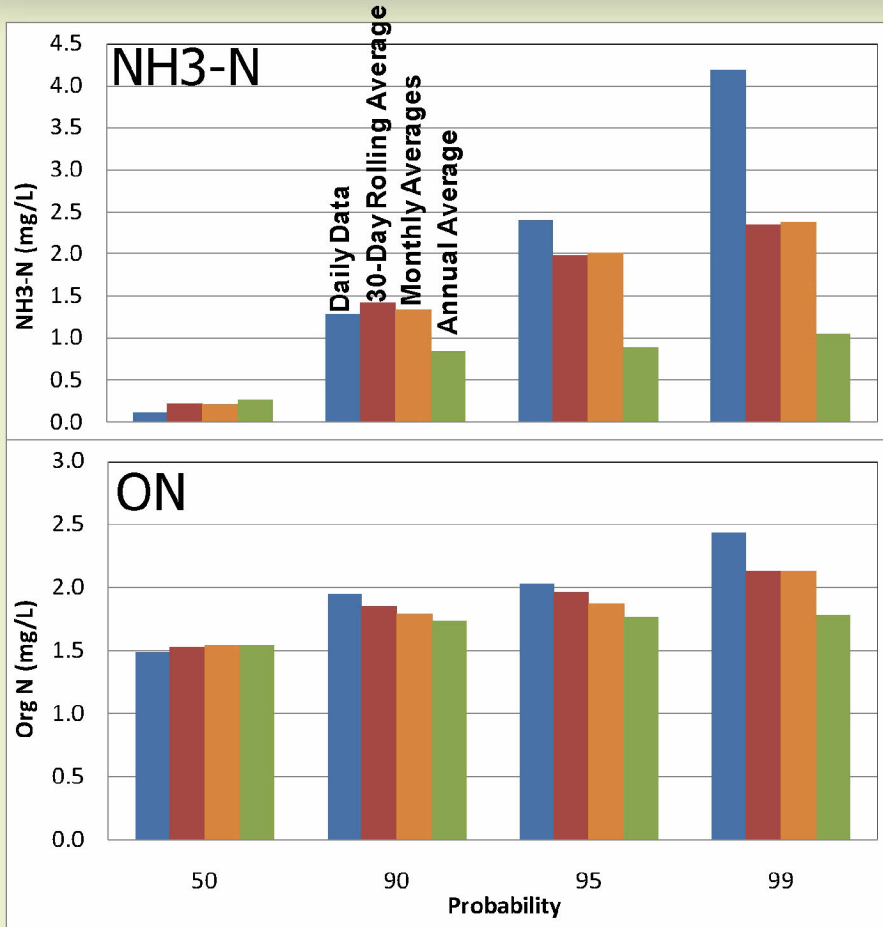
Example – TMWRF - N



Example – TMWRF



Example – TMWRF



- Design or Permitting
 - Have a target reliability (i.e. 95%)
 - Have a permit limit
 - “Assume” a CoV – process variability
 - Calculate the “Design Concentration

$$COR_{1-\alpha} = \frac{[\text{Design Conc.}]}{[\text{Permit Limit}]} = \text{Coefficient of Reliability}$$

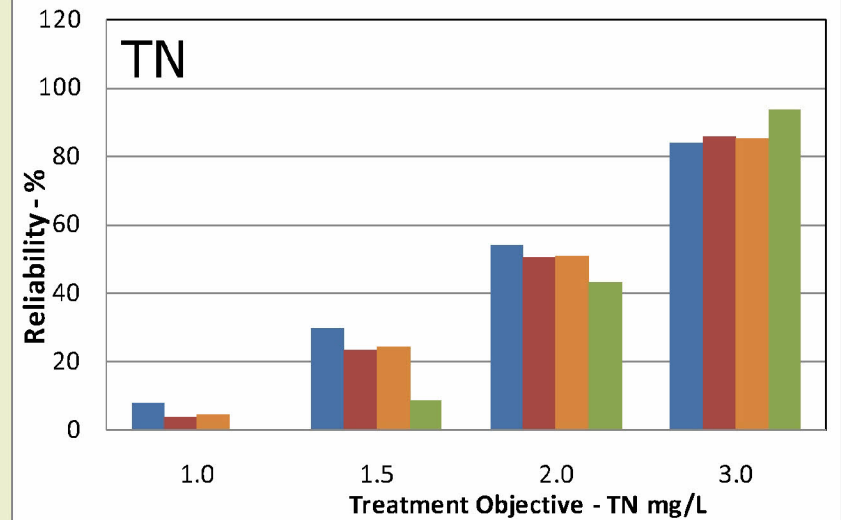
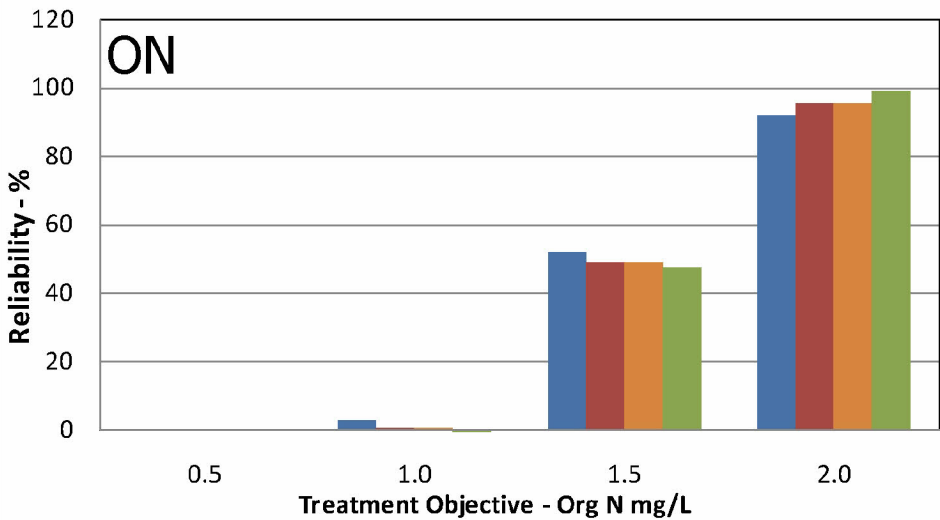
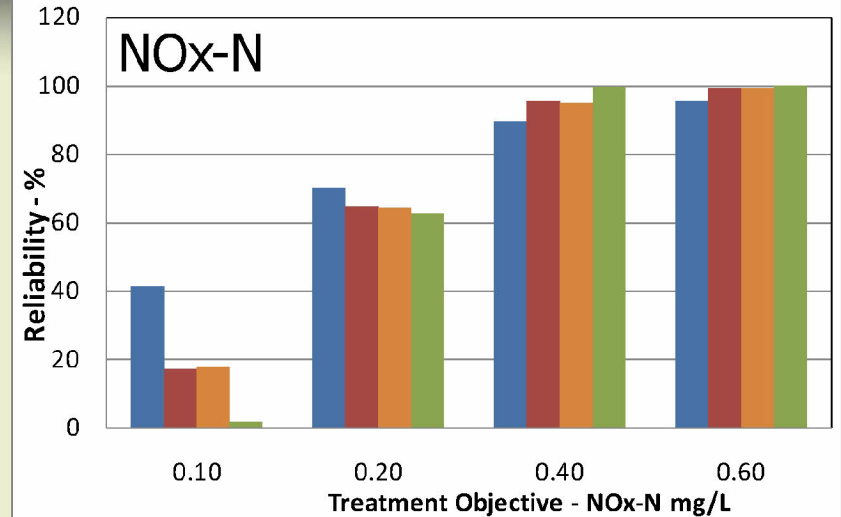
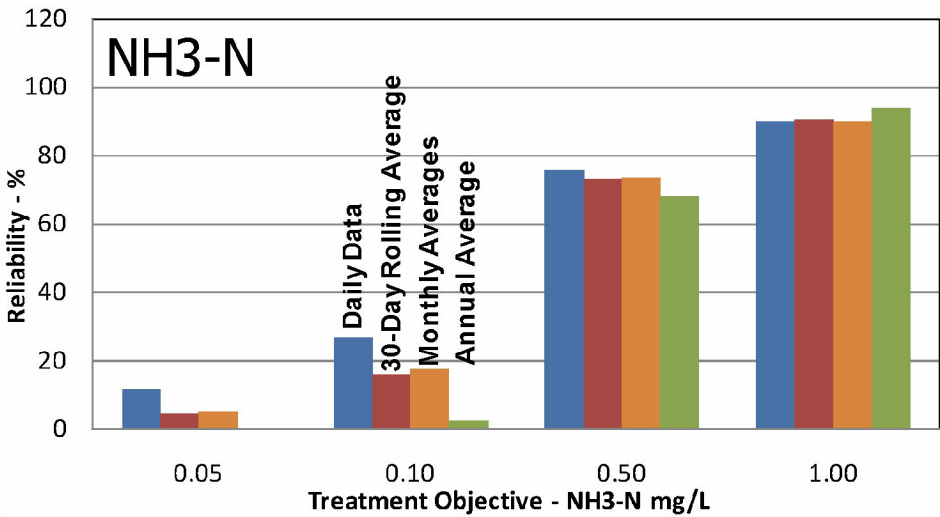
$$COR = \sqrt{CV^2 + 1} \times \exp\{-Z_{1-\alpha} \sqrt{\ln(CV^2 + 1)}\}$$

- Operating Plant – process reliability
 - Have deterministic permit limit
 - Have operating data
 - Calculate reliability of meeting permit limit with different averaging periods

$$Z_{(1-\alpha)} = \frac{\ln X_s - [\ln m'_x - \frac{1}{2} \ln(CV^2 + 1)]}{\sqrt{\ln(CV^2 + 1)}}$$

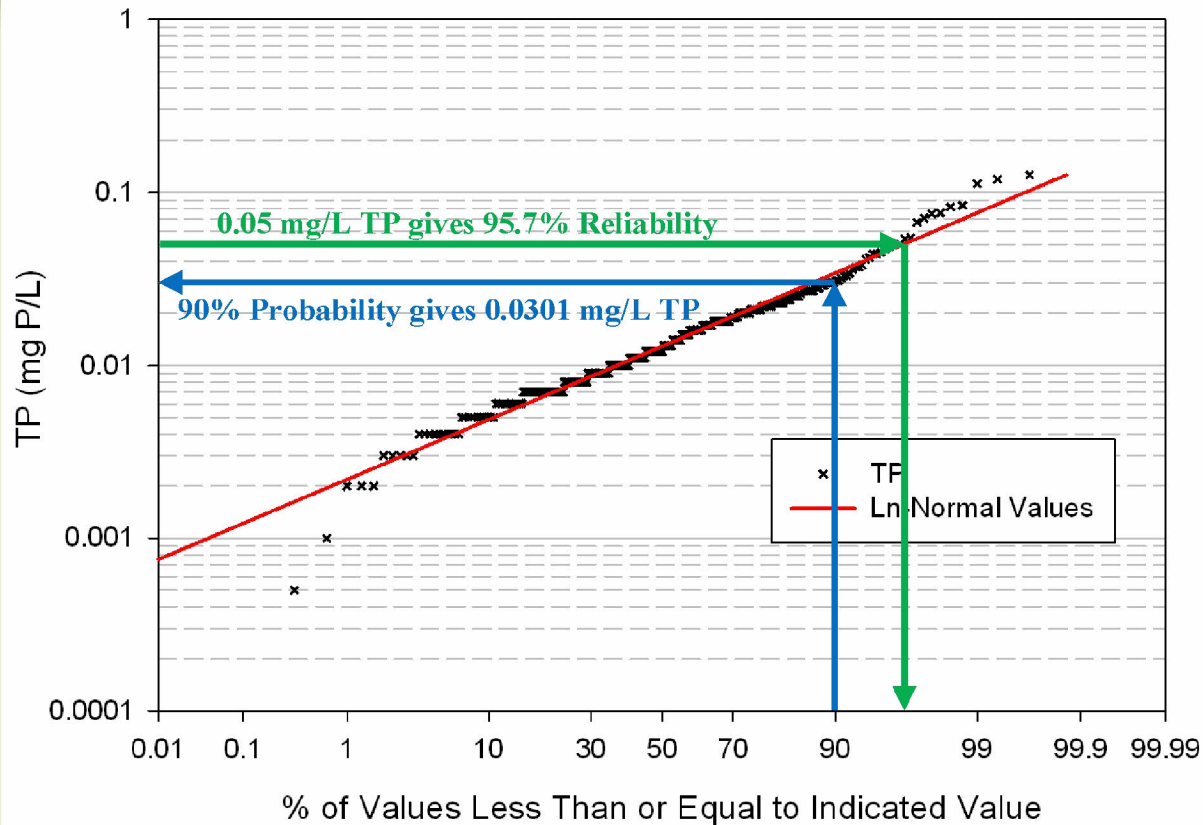
Oliviera, S. and Sperling, M. (2008) "Reliability Analysis of Wastewater Treatment Plants, *Water Research*, **42**, 1182.

Example – TMWRF



Note: The reliability calculation assumes the data is log-normally distributed.

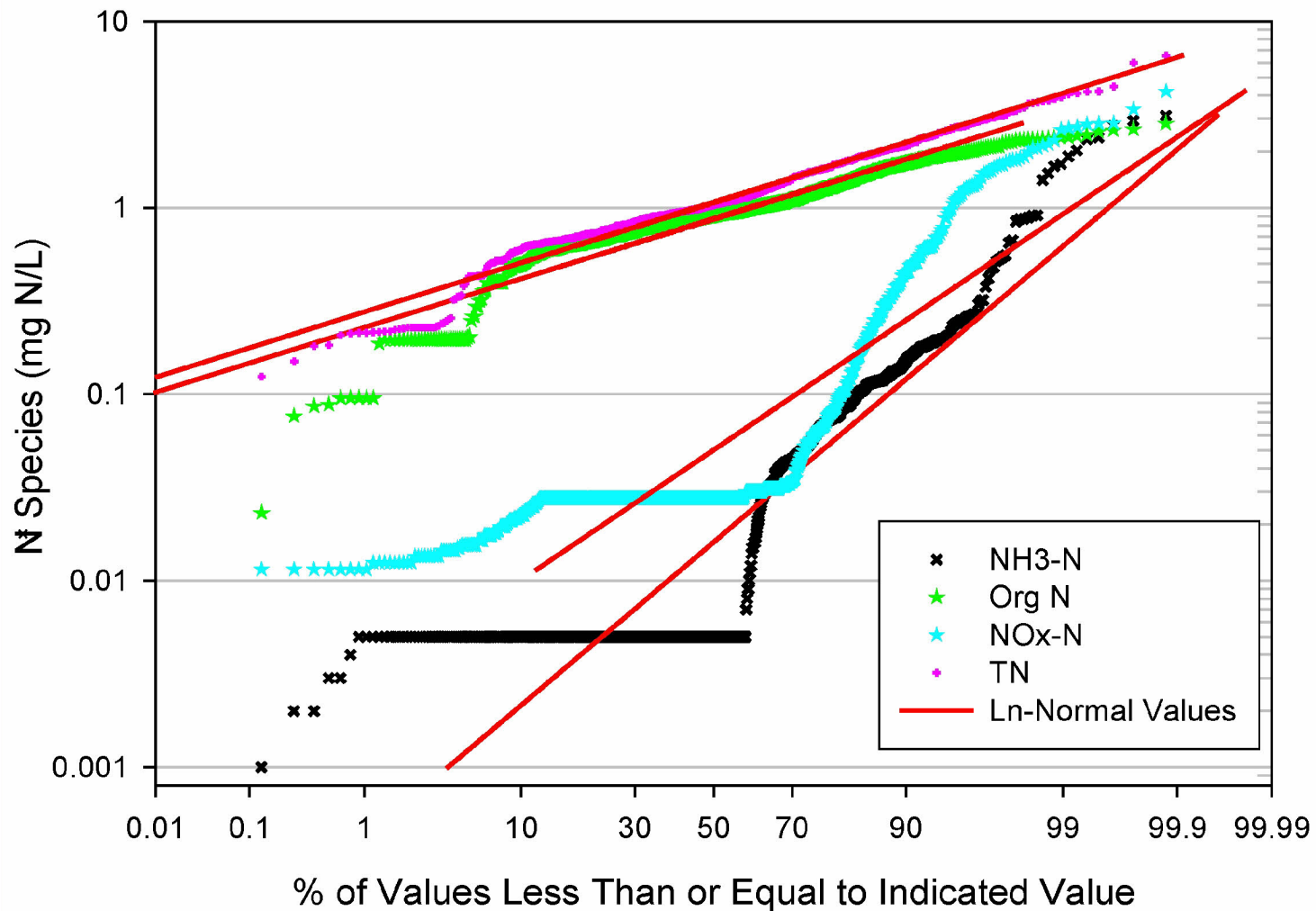
Probability = Reliability



Probability (%)	TP (mg/L)
50	0.0120
90	0.0301
95	0.0451
99	0.0843

Reliability (%)	TP (mg/L)
39.1	0.010
71.9	0.020
86.0	0.030
95.7	0.050

Log-Normal Distribution?



Probability and Reliability

Period	Basis (days)	Sample Frequency (days/year)	Percentile (%)
Max Day	1	365	99.7
-	-	-	99
Max Week	7	365	98.1
-	-	-	95
Max Month	30	365	91.8
-	-	-	90
Ann Avg	182.5	365	50.0

% Reliability for Daily Data at Specified Permit Limit

	TP Permit (mg/L)	TP Reliability (%)
Breckenridge - Iowa Hill	0.05	95.7
Cauley Creek	0.13	85.1
Clark Co	0.14	82.1
DCWASA	0.18	93.5
Gwinnett Co - FWHWRC	0.13	96.8
Rock Creek	0.10	72.3
	TN Permit (mg/L)	TN Reliability (%)
Fiesta Village	3	96.8
Orange Co - ERWRF	3	33.8
River Oaks	3	94.6
Truckee Meadows	2	54.1
WSSC Parkway	7	97.3

Another Consideration...

Table 2 – Number of Violations per Five Year NPDES Permit Period for Daily, Monthly and Annual Average Permits for Four Percentile Values

Percentile less than stated concentration	Daily (with daily sampling)	Monthly	Annual Average
50	912	30	3
90	183	6	0.5 (or 1 per 2 permit periods)
95	91	3	.25 (or 1 per 4 permit periods)
99	18	0.6 (or 1 per 2 permit periods)	0.05 (or 1one per 20 permit periods)

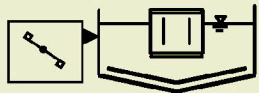
Process Building Blocks



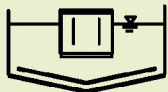
**Primary
Sedimentation**



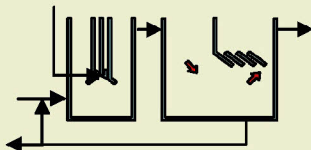
**Secondary
Sedimentation**



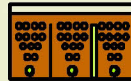
**Tertiary
Sedimentation
with External
Flocculation**



**Tertiary
Sedimentation
with Internal
Flocculation**



**Ballasted
Sedimentation
(Densadeg)**



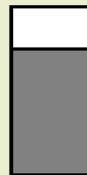
Aeration Basin



Mixed Reactor



**Nitrifying
Trickling Filter**



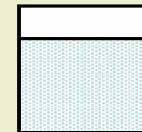
**Fluidized Bed
Reactor**



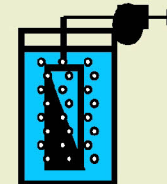
**Oxidation
Ditch**



**Biological
Aerated Filter
(Nitrifying)**



**Effluent Filter
(various types)**



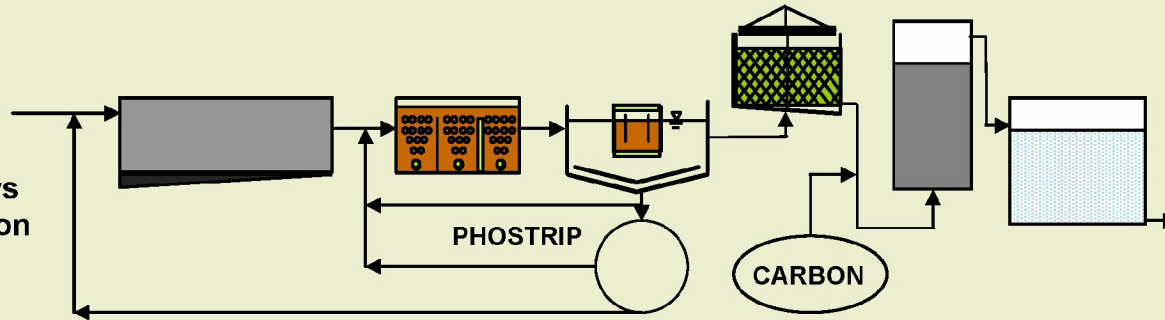
**Membrane
Filter (various
types)**



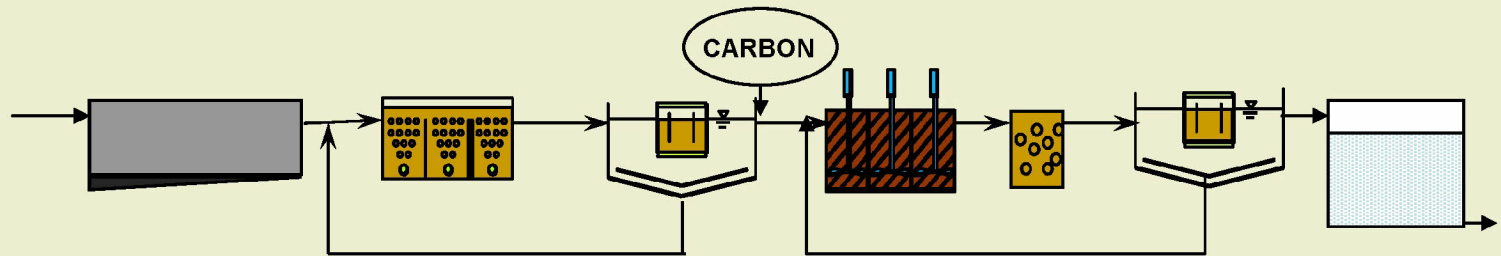
**Granular
Activated
Carbon
Column**

Separate Stage N Removal Flowsheets

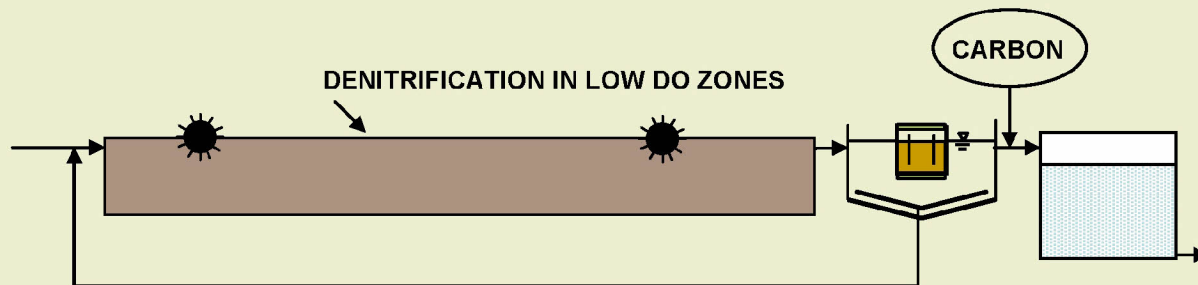
Truckee Meadows
Water Reclamation
Facility



River Oaks

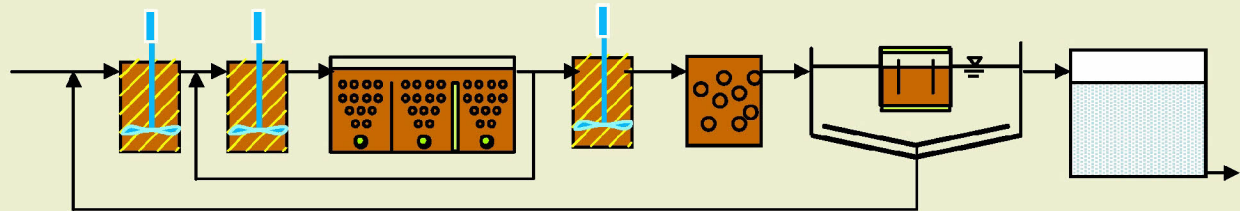


Fiesta Village

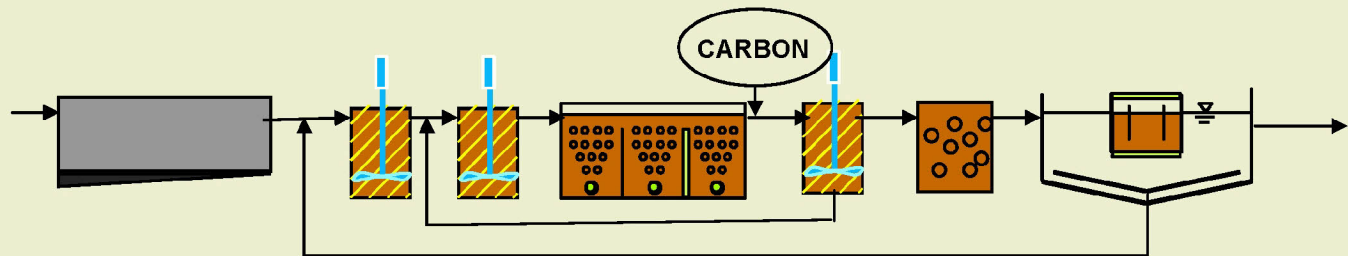


Combined N Removal Flowsheets

Eastern Water
Reclamation
Facility



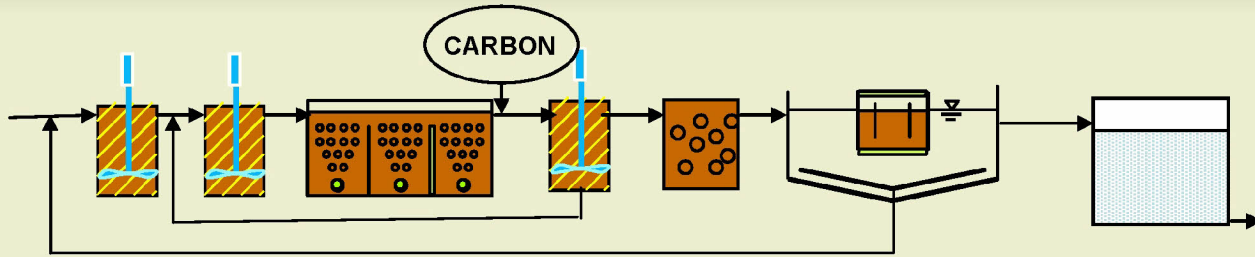
Parkway
WSSC



Separate Stage	TN, mg/L	Combined	TN, mg/L	Multiple Stage	TN, mg/L
Truckee Meadows Water Reclamation Facility, NV	4.0 3.1 (w/o five months impacted by toxic discharge)	Eastern Water Reclamation Facility	6.1	Fiesta Village, FL (denite filter)	2.2
River Oaks, FL	2.3	Parkway WSSC	5.1	5 A ² /O Plants with Denite Filters, FL	3.0
Howard F Curran, FL	3.0	10 Bardenpho Plants, FL	3.5		

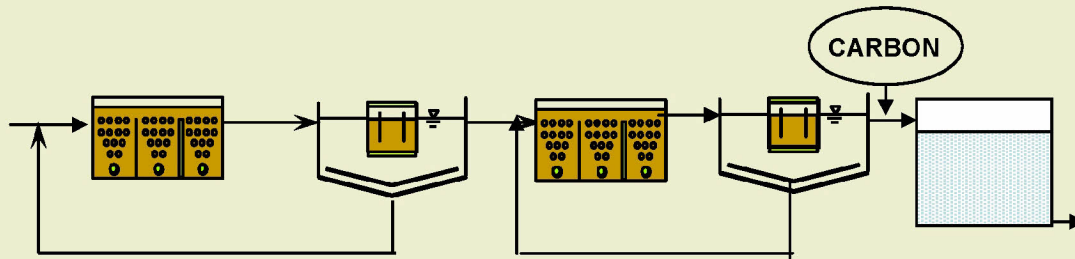
Key Flowsheets in Florida Survey

10 Combined N
Removal
Plants



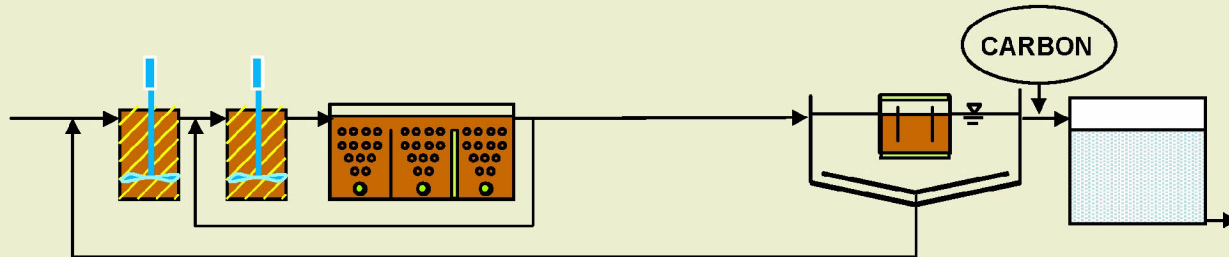
Bardenpho

1 Separate
Stage N
Removal



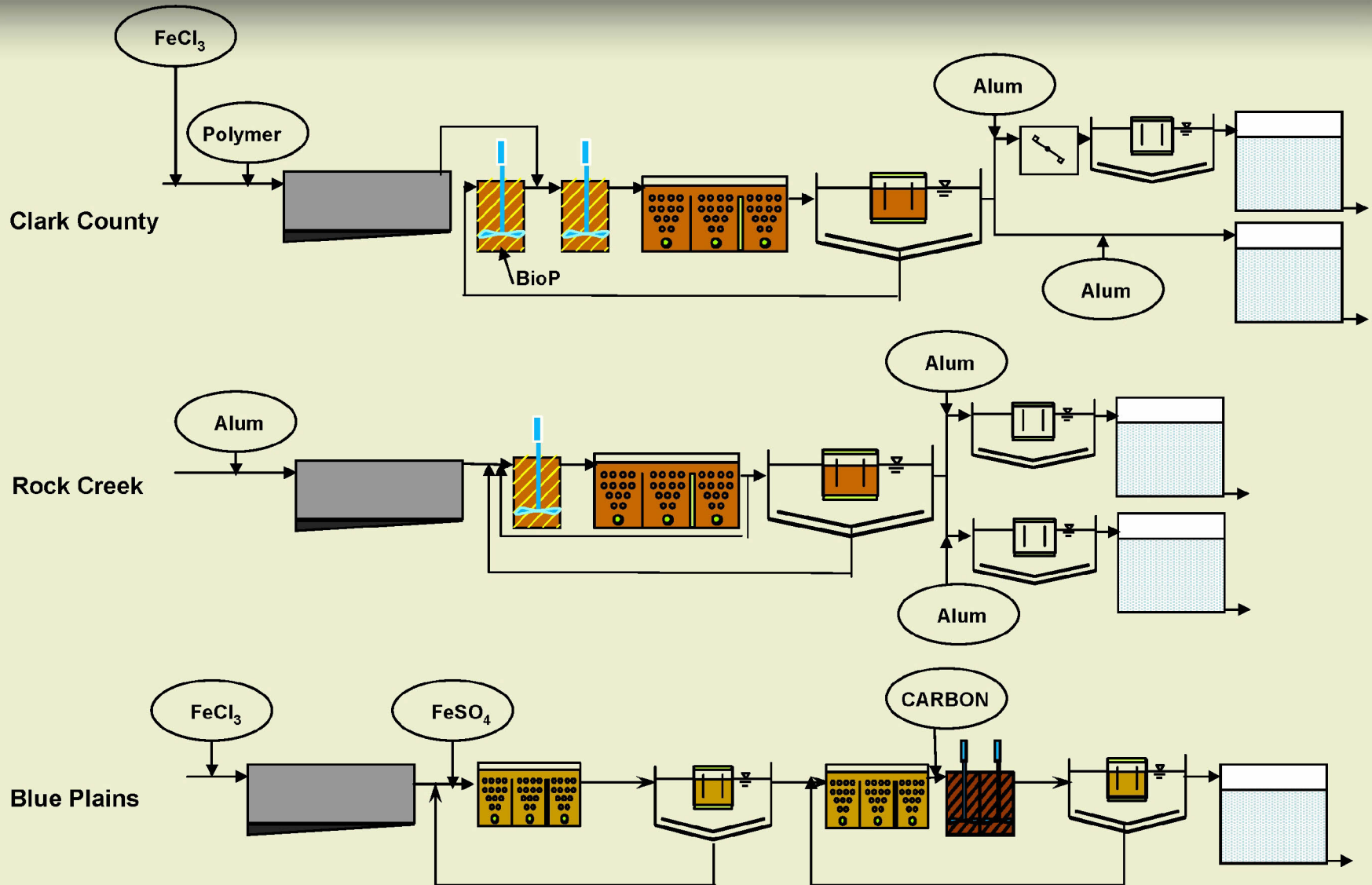
Howard F. Curran Plant, Tampa

5 Multiple
Stage N
Removal
Plants

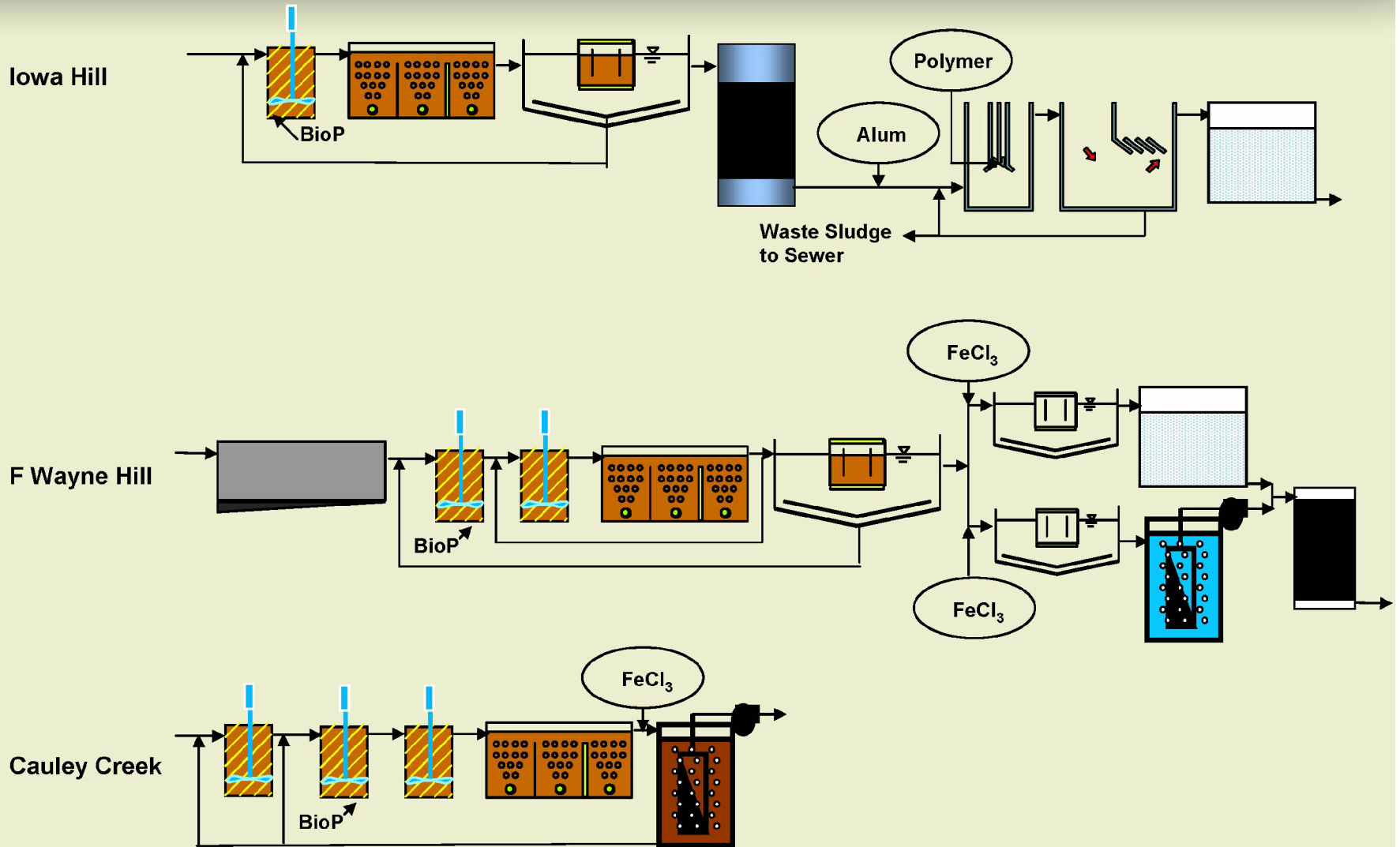


Phordox or A²/O Process

Multiple Stage Chemical Addition for P Removal



Single Stage Chemical Addition for P Removal



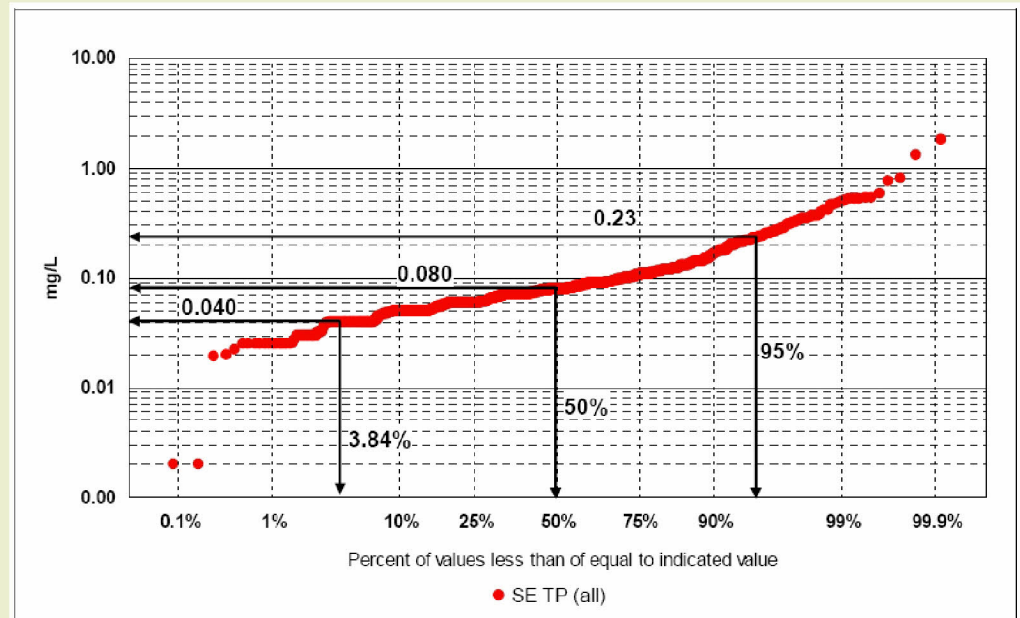
Recap of P Removal Technologies, TP, mg/L

Multiple Stage Chemical Addition	95 percentile Monthly average	Permit, monthly unless noted	Single Stage Chemical Addition	95 percentile Monthly average	Permit, monthly unless noted
Clark County, NV	0.151	0.20 (WLA)	Iowa Hill WRF, CO	0.0306	0.049 (annual)
Rock Creek, OR	0.151	0.10 (median)	Wayne Hill, Ga	0.090	0.13
Blue Plains, DC	0.161	0.18	Cauley Creek, Ga	0.117	0.13

Definition of LOT...

- Proposal suggested by Neethling, et al (2009)
 - Technology achievable limits (best, median, reliable)
 - Best: **TAL-14d** representing the 3.84th percentile
 - Median: 50th percentile
 - Reliable: 90, 95, 99th, etc percentile depending on the permit averaging period and the reliability required by the owner/operator

Neethling, JB; Stensel, H.D.; Parker, D.S.; Bott, C.B.; Murthy, S.; Pramanik, A.; Clark, D. (2009) What is the Limit of Technology (LOT)? A Rational and Quantitative Approach. *Proceedings of the WEF Nutrient Removal Conference*, Washington DC, Water Environment Federation, Alexandria, Virginia.

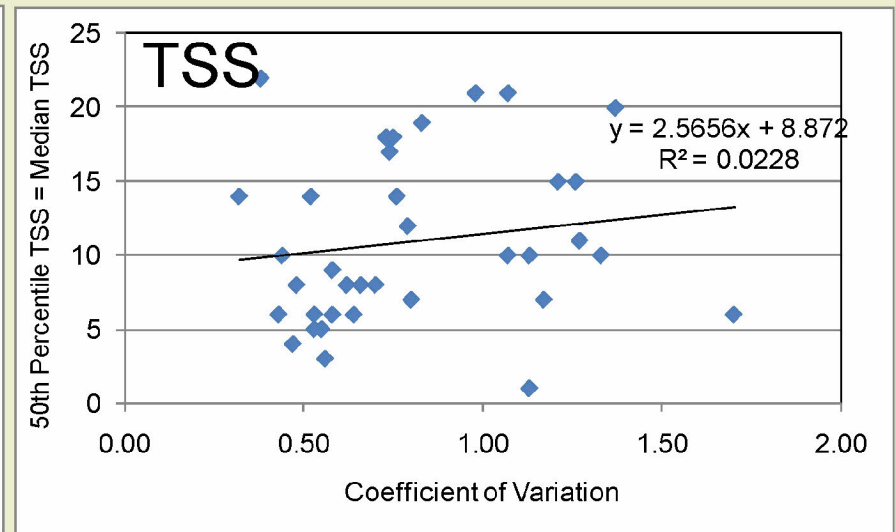
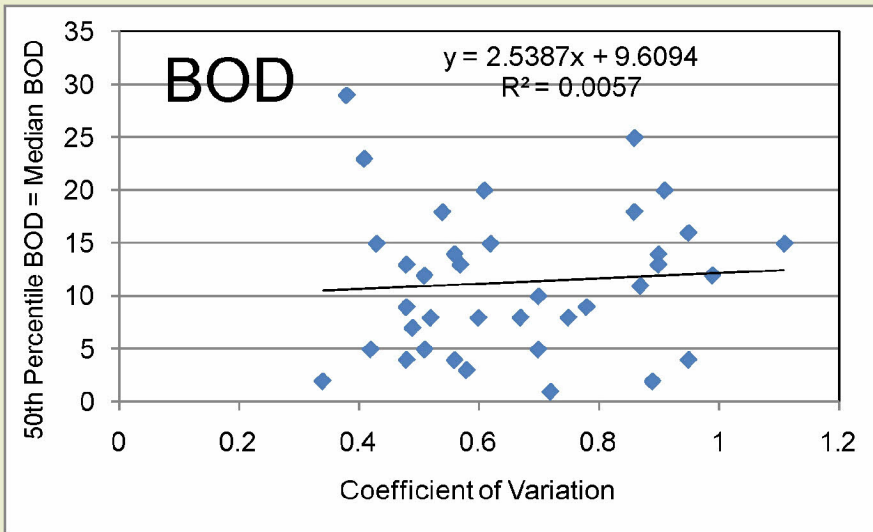


Definition of LOT...??

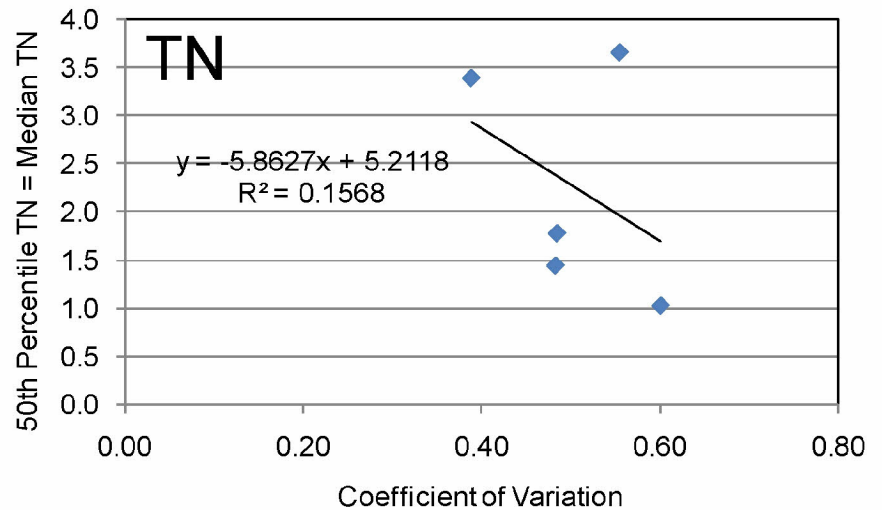
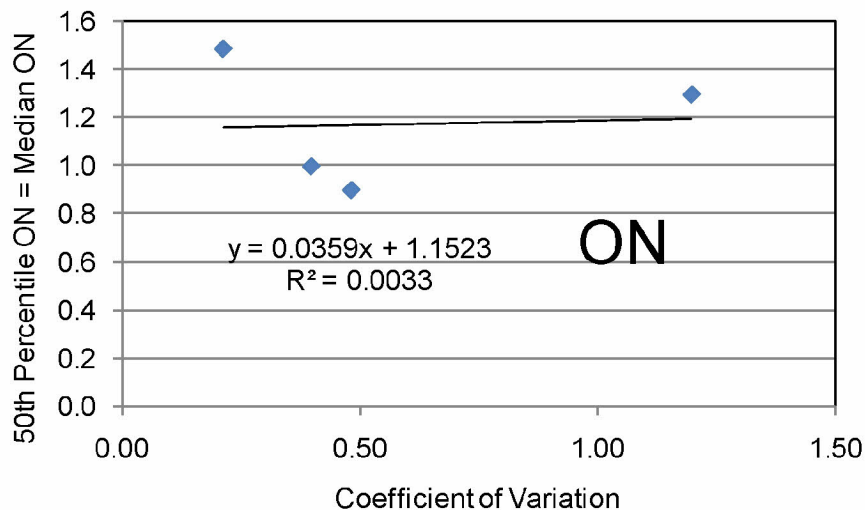
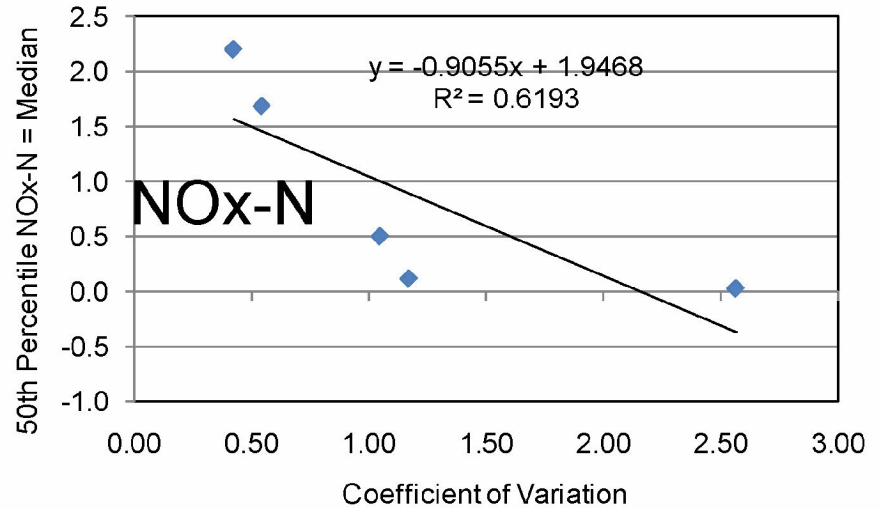
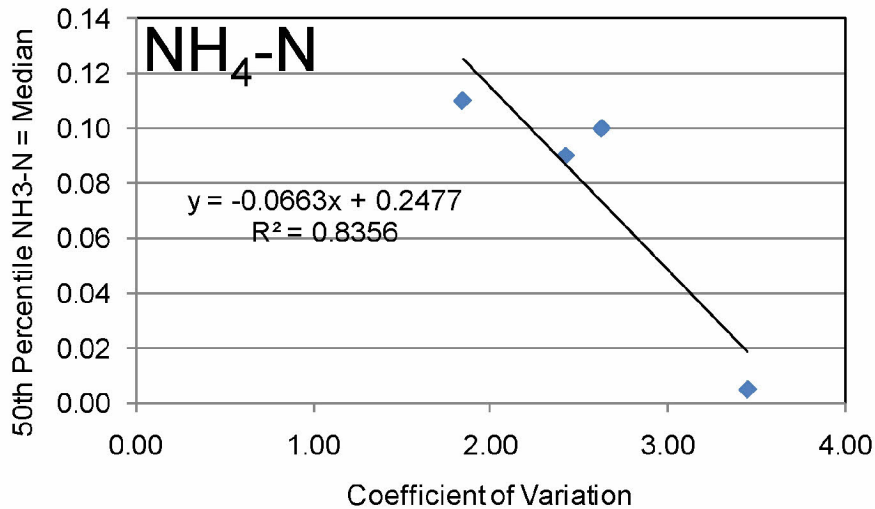
TN	Process	Permit ^c	14 d	50%	95%	14 d/50%	95%/50%
DCWASA	Nit	7.5 (4.2)	2.50	5.33	9.65	0.47	1.81
WSSC	Comb	7	2.10	3.40	6.20	0.62	1.82
Eastern EWRF Orange Co	Comb	5	2.09	3.67	8.18	0.57	2.23
Fiesta Village	Mult	3	0.21	0.83	2.11	0.26	2.54
Truckee Meadows	SepSt	2	1.20	1.77	4.26	0.68	2.40
River Oaks	SepSt	3.75	0.78	1.45	2.92	0.54	2.01

TP	Process	Permit ^c	14 d	50%	95%	14 d/50%	95%/50%
Rock Creek	2B	0.1	0.025	0.065	0.210	0.38	3.2
Gwinnett County	1B	0.13 (0.08)	0.020	0.040	0.110	0.50	2.8
DCWASA	2	0.18	0.020	0.080	0.180	0.25	2.3
CCWRD-Central Plant	2B	0.14	0.040	0.080	0.233	0.50	2.9
CCWRD-AWT	2B	0.14	0.040	0.082	0.176	0.49	2.1
Cauley Creek	1B	0.13	0.040	0.080	0.160	0.50	2.0
WSSC	1	1	0.050	0.140	0.650	0.36	4.6
Eastern EWRF Orange Co	1B	2	0.100	0.190	0.630	0.53	3.3
Breckenridge	2B	0.050	0.004	0.012	0.045	0.33	3.8

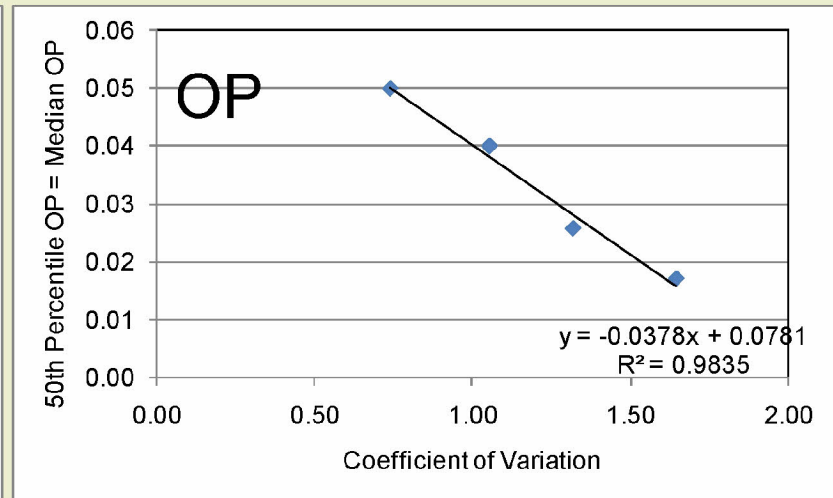
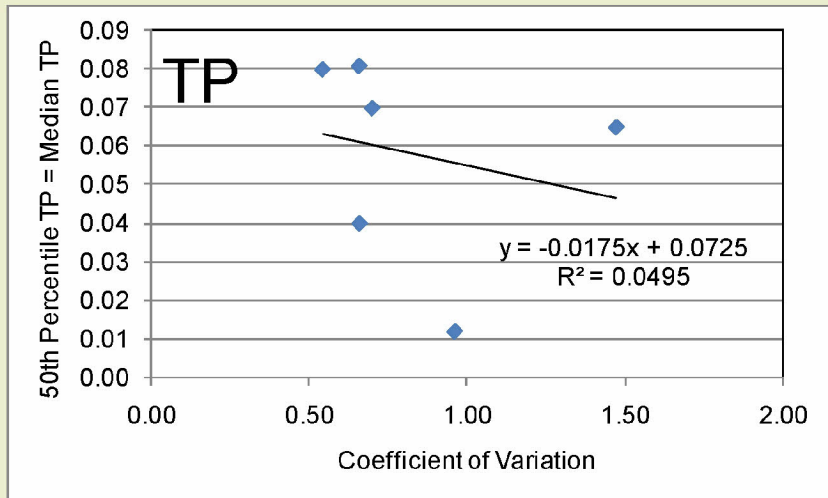
This what we would expect – lower effluent TSS and BOD indicates process stability...



This trend is quite the opposite of what might be expected...



This trend is quite the opposite of what might be expected...



- Max Day, Max Week, Max Month, Max Year
 - Extend averaging period to reduce variability and improve reliability
- True Mass Load Limit
 - In some states, an annual mass load limit is being combined with a monthly or annual concentration-based limit (technology-based)
 - Annual mass load limits provide some flexibility
- Permit based on Median or Mean + Reliability
 - For example:
 - TN permit limit = 3 mg/L based on median calculated from daily data (means 50% reliability)
 - TN permit limit = 3 mg/L based on annual average with 90% reliability
 - etc
 - Reliability calculation either directly from data or from log-normal approximation
 - Mean is susceptible to upset conditions
- Watershed-based permitting – Nutrient Trading
 - Example Programs in Connecticut and Virginia (point to point)
 - Point to non-point trading is developing more slowly

What is Achievable?

- **Current permitting approach requires near-100% reliability**
 - Not applicable for limits near the LOT (particularly when the limit is technology-based)
 - Must consider the increase in effluent variability as we push to lower concentration
 - Too many variables affect the definition of LOT in terms of a strict numerical limit
 - Corollary – Suppose drinking water treatment plants were required to meet a MCL for Total Coliform of 0 cfu/100 mL?
- **Recommendation**
 - Further assessment of probability/reliability at plants now meeting “stringent” nutrient limits
 - Limits could specified with a measure of reliability
 - Reliability specification depends on site-specific variables

Questions?

- Charles B. Bott, VMI (transitioning to HRSD)
 - cbott@hrsdc.com
- Denny S. Parker, Brown and Caldwell
 - DParker@BrwnCald.com
- JB Neethling, HDR
 - JB.Neethling@hdrinc.com
- For more information:
 - <http://www.werf.org/AM/Template.cfm?Section=Nutrients>

- Probability and Reliability
 - Evaluate concentration that would be met at a given probability
 - Determine the reliability that is achieved at a given concentration
- Reliability
 - Can be calculated assuming log-normal distribution applies
 - Or determined directly from data on a log-probability plot
- An assessment of reliability provides a quantitative mechanism for addressing the many variables that could affect a plant's ability to meet a given permit limit
 - There is an inherent consideration of process variability (e.g. CoV) built into a probability/reliability calculation

N Reliability

	TN Permit (mg/L)	TN Reliability (%)
Fiesta Village	3	96.8
Orange Co - ERWRF	3	33.8
River Oaks	3	94.6
Truckee Meadows	2	54.1
WSSC Parkway	7	97.3

NH4-N Obj. (mg/L)	NH4-N Reliability (%)
0.5	97.4
0.5	59.9
0.5	NA
0.5	76.0
0.5	86.2

NOx-N Obj. (mg/L)	NOx-N Reliability (%)
0.5	92.4
0.5 / 2.0	1.3 / 68.6
0.5	53.0
0.5	93.5
0.5 / 2.0	0.0 / 41.3

ON Objective (mg/L)	ON Reliability (%)
1.0	59.3
1.0	48.4
1.0	NA
1.0 / 1.5	3.1 / 52.0
1.0	58.5

P Reliability

	TP Permit (mg/L)	TP Reliability (%)
Breckenridge - Iowa Hill	0.05	95.7
Cauley Creek	0.13	85.1
Clark Co	0.14	82.1
DCWASA	0.18	93.5
Gwinnett Co - FWHWRC	0.13	96.8
Rock Creek	0.10	72.3

OP Objective (mg/L)	OP Reliability (%)
0.10	NA
0.10	88.2
0.10	91.8
0.10	88.8
0.10	NA
0.10	92.6

- All plants with low TN effluent requirements and all produce low values on average.
- Marginally higher ammonia values at Truckee Meadows than Florida Plants likely due to higher LOT for Nitrifying Trickling Filters compared to activated sludge systems
- Two Florida sites have aerobic storage/digestion with off site disposal with minimal returns whereas Truckee Meadows has anaerobic digestion and dewatering.
- Higher organic N at Truckee Meadows than Florida plants could be due to solids processing returns from digestion and dewatering or due to differences in the degree which the main stream biological processes create rDON. *More research needed on this issue.*
- Higher TN at Truckee Meadows during five months with toxic upsets expected to be nonrecurring. If those months were excluded, 95 percentile monthly TN likely would be reduced by 0.9 mg/L if this had not occurred.

- Expected differences due to climatic conditions not seen comparing the two plants.
- 95 percentile values for monthly averages were 6.1 mg/L for Eastern and 5.1 mg/L for Parkway. This is not the LOT for the Bardenpho process. A survey of 10 Florida Bardenpho plants found 95 percentile value of 3.5 mg/L for monthly average TN.
- Elevated ammonia and organic N seem the probable cause for elevated TN at Eastern and that elevated nitrate is the cause for elevated TN at Parkway.

- LOT is statistically defined for this technology.
- Similarity in performance likely due to effluent TP primarily dominated by physical/chemical processes rather than biological processes.

- All plants either achieve (or nearly) 0.1 mg/L TP on an monthly basis 95 percent of time.
- All the plants benefit from upstream BioP to reduce chemical requirements.
- Iowa Hill may benefit by lack of solids processing and solids return flows at the plant. Both of the other plants have solids processing on site.
- Cauley Creek's MBR flowsheet may suffer relative to the other flowsheets as all the biological and chemical reactions are combined in the activated sludge step.
- Permit limits vary between the plants, impacting the technologies selected and chemical dosages.

- Processes tailored and operated to meet limits
- Single Stage able to meet lower limits than Multiple Stage Chemical Addition
- However, two of the Multiple Stage plants (Rock Creek and Clark County) have tertiary clarifiers and might be able to meet lower TP limits if chemical dosages were adjusted.

95 Percentile TN values (mg/L) for Separate Stage N Removal Plants

Plant	Daily Data	Rolling 30-day Average	Monthly Average	Annual Average
Truckee Meadows Water Reclamation Facility, NV	4.27	4.27	4.00	2.83
River Oaks, FL	2.92	2.27	2.27	1.89
Fiesta Village, FL	2.71	2.26	2.20	1.71

95 Percentile TN values (mg/L) for Combined N Removal Plants

Plant	Daily Data	Rolling 30-day Average	Monthly Average	Annual Average
Eastern Water Reclamation Facility	8.20	6.66	6.12	4.49
Parkway WSSC	6.2	5.26	5.07	4.29

Technology	95 Percentile Monthly TN Value, mg/L
Combined	3.5
Separate Stage	3.1
Multiple Stage	3.0

Or does this give undue weight to the moderate climate experience of Florida?

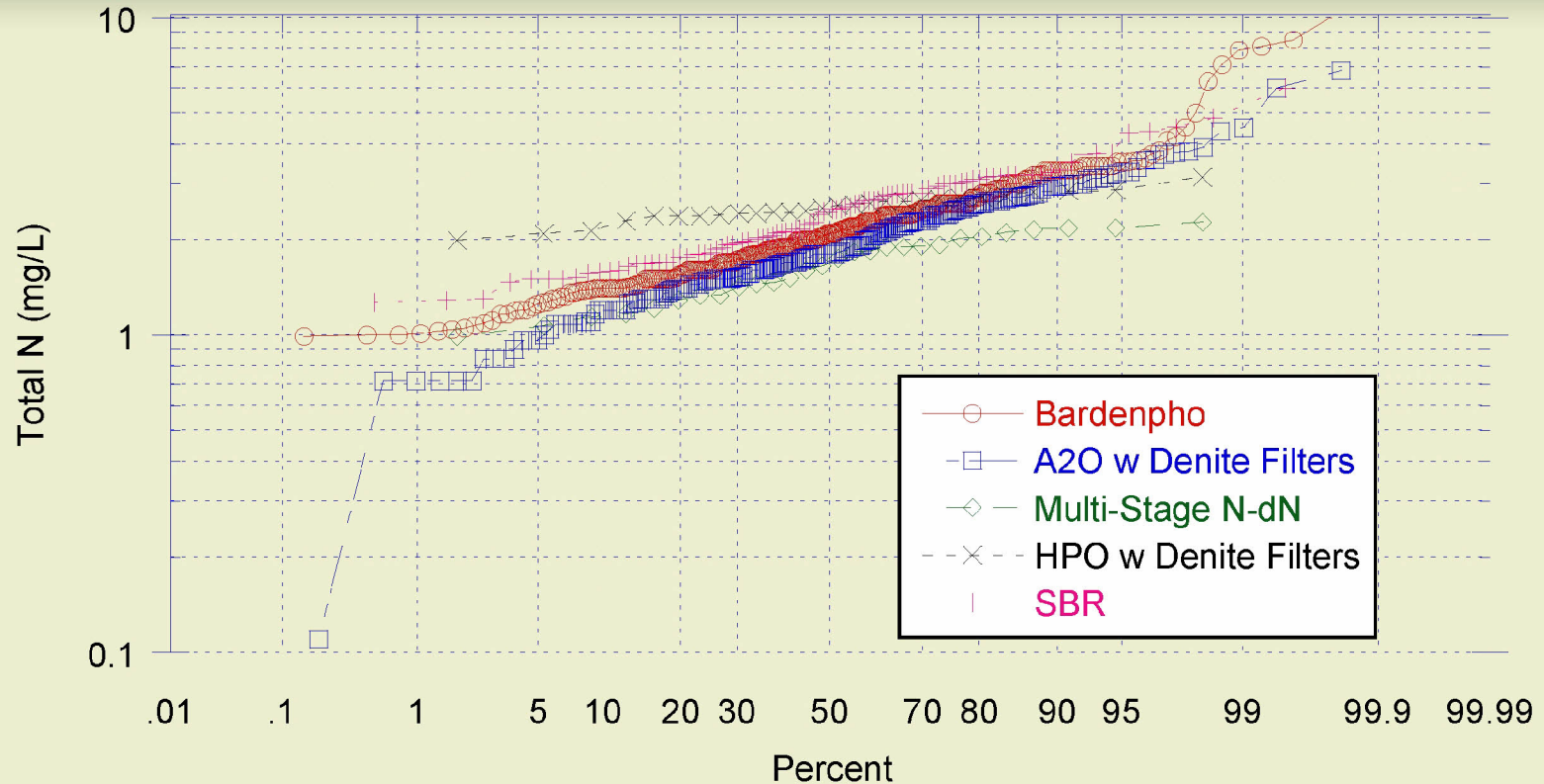
95 Percentile TP values (mg/L) for Multiple Stage Chemical Addition for P Removal Plants

Plant	Daily Data	Rolling 30-day Average	Monthly Average	Annual Average
Clark County, NV	0.200	0.157	0.151	0.109
Rock Creek, OR	0.210	0.174	0.151	NR, dry months only
Blue Plains, DC	0.180	0.158	0.161	0.106

95 Percentile TP values (mg/L) for Single Stage Chemical Addition P Removal Plants

Plant	Daily Data	Rolling 30-day Average	Monthly Average	Annual Rolling Average
Iowa Hill WRF, CO	0.0451	0.0396	0.0306	0.0268
Wayne Hill, Ga	0.110	0.093	0.090	0.062
Cauley Creek, Ga	0.160	0.121	0.117	0.095

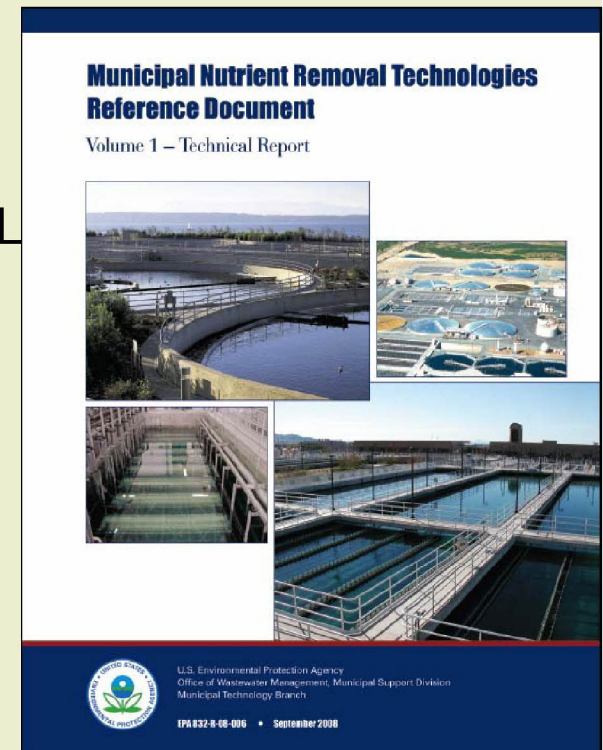
Florida Nitrogen Removal Facilities: Probability Statistics for Various Types of Plants



From: Jimenez et al., "Full-Scale Operation of Large Biological Nutrient Removal Facilities To Meet Limits of Technology Effluent Requirements: The Florida Experience," WEFTEC07.

Methods for Assessing Reliability...

- Coefficient of Variation
 - $\text{CoV} = [\text{Standard Deviation}] / [\text{Mean}]$
 - Addresses only process variability, not reliability
 - Doesn't take into account permit limit or treatment objective
- Example:
 - **Permit = 3 mg/L TN (annual average)**
 - Plant A → meets an annual average of **4 mg/L** with a CoV of **20%**
 - Plant B → meets an annual average of **2.5 mg/L** with a CoV of **90%**
- Probability plots and percentile statistics
 - Needs to be formalized, defined...



From Chorafas, D. (1960) "Statistical Processes and Reliability Engineering, Van Nostrand Co.

- Describing definition of reliability of a system
 - “the ability to perform the specified requirement *free from failure*”
 - “the probability of adequate performance for *at least a specified period of time under specified conditions*”

$$\text{Reliability} = 1 - \text{Probability}_{(\text{failure})}$$

$$= 1 - \text{Probability}_{(\text{effluent conc.} > \text{limit})}$$

From: Niku, S., Schroeder, E. and Samaniego, F. (1979) "Performance of Activated Sludge Processes and Reliability- Based Design, *J. Water Poll. Control Fed.*, **51**, 2841.

- The lack of precise design methods, uncertainties, and the dynamic nature of biological waste treatment processes lead the designer to overbuild units and to overdesign processes.
- Economical pressure or lack of understanding of the variables that affect effluent quality have caused inadequate processes with an incapability to perform efficiently.
- Design engineers must be able to estimate the expected effluent quality and its variations for a given treatment process.
- Uncertainties and their significance on process performance can be analyzed systematically using methods of probability.
- A probabilistic approach for design provides a consistent basis for analysis of uncertainty.

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Performance of activated sludge processes and reliability-based design

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Since 1974 explicit performance standards have been placed on most activated sludge processes in the U.S. The Federal Water Pollution Control Act Amendments of 1972 (PL 91-509) establish the basis for effluent quality regulation to ensure the quality of receiving waters. Discharge requirements vary from plant to plant, but in general are at least as strict as secondary treatment guidelines followed by the U.S. Environmental Protection Agency. Current regulations often require very high average treatment efficiencies and also restrict variations from the allowable average concentrations. In most cases penalties have been set for violation of these requirements.

Currently, activated sludge wastewater treatment is the most commonly used process for treating wastewaters. Conventional criteria and design procedures used in the design of municipal and industrial wastewater treatment processes assume steady-state conditions. These processes usually operate under steady-state conditions, however. Fluctuations in influent, toxic, environmental conditions, and in plant biological and operational variations are given little consideration in the system designs. The lack of precise design methods, uncertainties, and the dynamic nature of biological waste treatment processes lead the designer to overbuild units and to overdesign processes. Economical pressure or lack of understanding of the variables that affect effluent quality have caused inadequate processes with an incapability to perform efficiently.

To produce a high effluent quality and to meet the requirements at minimum cost, design engineers must be able to estimate the expected effluent quality and its variations (that is, the relationship between the nominal high values and the average values) for a given treatment process. Uncertainties and their significance on process performance can be analyzed systematically using methods of probability. A probabilistic approach for design provides a consistent basis for analysis of uncertainty.

In a technical definition, the essential concept of reliability is "probability of success" or "probability of adequate performance," that is, the percent of the time that effluent concentrations meet the requirements.

Reliability = $1 - P(\text{failure}) = 1 - P(\text{effluent conc.} > \text{requirement})$ (2)

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